Deep Ocean Sound Propagation in Environments with Strong Range Dependence

Ilya A. Udovydchenkov
Applied Ocean Physics and Engineering Department, MS #9
Woods Hole Oceanographic Institution
Woods Hole, MA, 02543
phone: (508) 289-3680 fax: (508) 457-2194 email: ilya@whoi.edu

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LONG-TERM GOALS

Our long-term scientific goal is to understand the basic physics of low-frequency long-range sound propagation in the ocean and the effects of environmental variability on signal stability and coherence. We seek to understand the fundamental limits to signal processing imposed by ocean variability to enable advanced signal processing techniques, including matched field processing and other adaptive array processing methods.

OBJECTIVES

The principal objectives of this work are: 1) to further develop the theory of underwater sound propagation in realistic deep ocean environments with an emphasis on mode coupling in environments with strong range-dependence; 2) to investigate the importance of resonant forward scattering of sound in deep ocean environments resulting from interactions with either mesoscale structure or internal tides; and 3) to test theoretical predictions using measurements made during the NPAL Philippine Sea Experiment, including both the 2009 Pilot Study/Engineering test and the larger 2010-2011 Philippine Sea Experiment.

APPROACH

Our approach to addressing these objectives builds on prior theoretical development, numerical modeling and analysis of acoustic data recorded during the Long Range Ocean Acoustic Propagation Experiment (LOAPEX). Our work involves data analysis, testing and further development of existing theory relating it to the PhilSea experimental conditions, and extensive propagation modeling. These topics are being investigated by I. Udovydchenkov at WHOI as a postdoctoral fellow under the supervision of T. Duda in collaboration with NPAL investigators at RSMAS (M. Brown), APL/UW (J. Mercer, B. Howe and R. Andrew) and SIO (P. Worcester and M. Dzieciuch). The efforts are directed towards quantifying acoustic fluctuations observed in the data, providing a theoretical basis for understanding these observations and making predictions relevant to ongoing experiments. Theoretical work relies heavily on the modal description of the acoustic field and exploitation of links between asymptotic mode theory and ray theory, i.e., aspects of ray-mode duality. A theory of modal group time spreads (a modal group arrival is a contribution to a transient wave field corresponding to a fixed mode number) has been previously developed [1]. Relevant theoretical extensions are being developed

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with emphasis on improving our understanding of the connection between environmental variability and wave field structure and stability in environments with strong range dependence.

WORK COMPLETED

1. Modal analysis of LOAPEX measurements

Two papers describing modal analysis of LOAPEX measurements have been written. The first paper focuses on analysis of energy contained in low mode numbers and uses the data collected on the shallow vertical line array only; the second paper describes the processing of the LOAPEX data using the combined shallow/deep pseudo-array.

2. Reduction of environmental mismatch

It has been shown that some of the observed disagreement between measured and simulated mode processed LOAPEX wave fields can be reduced by performing simulations in a reconstructed sound speed profile. The reconstruction (inversion) algorithm uses as input the travel times of modal group arrivals obtained from the mode processed LOAPEX measurements; the theoretical framework for this procedure was originally described by Munk and Wunsch [2]. The inversion algorithm has been implemented and it has been demonstrated that use of the inverted profile results in better agreement between measured and simulated wave fields. In addition, the algorithm has been revisited in order to address some issues related to the stability of the inversion. It was discovered that uniqueness condition requiring the knowledge of the sound speed profile either below or above the sound channel axis sometimes can be replaced with other conditions, which are easier to satisfy with available environmental data. Figure 1 shows simulated and measured wave field intensities in the depth-time plane together with mode-processed results. This figure was constructed using the sound speed profile computed from UCTD measurements in the upper ocean matched with climatological data in deep ocean. Figure 2 shows several different sound speed profiles estimated from CTD measurements made during LOAPEX experiment together with the inverted profile. Tomographic inversion results are shown in Fig. 3. This figure illustrates the correction to the theoretically predicted modal group arrival times obtained from the inversion. This work was included as part of the second LOAPEX analysis paper.

3. Low mode number scattering of acoustic energy

It is shown in [1] that the scattering-induced contribution to a modal group time spread grows in range as r^(3/2). However, the derived expression for the scattering-induced contributions is inaccurate for modes with low mode numbers. Low mode numbers require special care because, unlike high mode numbers, energy in the gravest mode can be scattered only into higher mode numbers. A theoretical framework for treatment of near-axial scattering was presented in [4] and [5]. However, an attempt to obtain a simple analytical expression for the correction to modal group time spread estimates was not successful. While corrections to modal group time spread estimates within the framework mentioned above were computed numerically, they were of a limited use. These corrections do not account properly for the travel time bias associated with low order mode scattering and also apply only to a single mode starter acoustic field. In order to overcome these difficulties a simple numerical model has been developed (together with M Brown) that allows prediction of intensity distributions of energy among low order modes. This model improves the estimate of modal group time spreads for low order modes and correctly predicts a sharp trailing edge of intensity distributions observed in the data. Figure

4 provides a comparison of the mode-processed LOAPEX data (75 Hz, 800m source depth), numerical PE (parabolic equation) simulations and theoretical predictions using the newly developed model. Also modal group time spreads and skewnesses of energy distributions are compared in that figure and good agreement is observed between data, numerical simulations and theoretical predictions. This work is being presented at the NPAL workshop.

4. Mode processing using a deficient receiving pseudo-array

The mode processing associated with the estimation of modal group arrivals requires that the wave field be measured on a vertical array that is both long and dense. In the LOAPEX experiment vertical receiving arrays on two moorings were used to collect data. These moorings were separated by approximately 5 km. Because of the horizontal separation between the moorings there are phase differences between data recorded on the two vertical arrays. These phase errors are mode number dependent and cannot be corrected. The mode processing method has been revisited and it was concluded that for the purpose of estimating modal group time spreads for high order modes in the LOAPEX experiment it is necessary to complement the existing measurements with model predictions. A piecewise-coherent mode processing method was proposed as a suitable method for estimating durations of modal group arrivals for high order modes. The results from piecewise-coherent mode processing are shown in Fig. 5.

5. Mode filtering

It has been discovered during analysis of the LOAPEX data that many commonly used mode filters, while being optimal in some sense may have other significant shortcomings. In particular, most of those filters violate the energy conservation condition. The energy conservation directly follows from the orthonormality of the acoustic normal modes. This observation becomes obvious if one notes that a statement analogous to Parceval's theorem which is usually applied in Fourier analysis holds for the generalized Fourier series with any basis functions that form a complete orthonormal set (and acoustic normal modes form such a set). A paper [6] discussing the importance of energy conservation condition in mode filtering algorithms has been published and this work has been presented at 159th ASA Meeting in Baltimore, MD.

6. Resonant forward scattering

Traditional theoretical studies of the forward scattering of sound treat scattering events as uncorrelated events. Recently, we (I Rypina, M Brown and myself) have explored a conceptually very different theoretical framework in which scattering is controlled by resonant scattering. Resonances are excited between background rays, which are periodic in range, and periodic structures in the sound speed perturbation. Because modes can be associated with interfering up- and down-going rays, the resonant scattering approach is also applicable to the description of mode coupling. For a narrowband (in horizontal wave number) perturbation only a small number of resonances are excited, while internal-wave-induced perturbations, which contain many length scales, excite many resonances. A general expression for resonance widths has been derived [3]. Exceptional deep ocean conditions are found in the vicinity of submarine ridges, which serve to generate internal tides that are both highly directional and have a narrow horizontal wave number spectrum. We expect the internal tides to be one of the dominant sources of ocean variability during 2009/2010 Philippine Sea experiment.

7. Mode coupling in the presence of strong mesoscale variability and internal tides

In the past work related to the analysis of the data collected in the Eastern North Pacific ocean it was common to model the acoustic environment as a range-independent (or slowly-varying range-dependent) background sound speed structure with small scale range- and depth-dependent perturbation, due for example to internal waves, superimposed. However, in the Philippine Sea it is expected that strong mesoscale variability and internal tides will play an important role in acoustic scattering. It was noted that slightly different decomposition of the environment into background terms and a perturbation term may be advantageous. The decomposition represents inverse squared of the sound speed (rather than the sound speed) as a sum of depth- only dependent term, range-only dependent term and small depth- and range-dependent perturbation. It is expected that with use of this decomposition some of the mesoscale variability can be absorbed into the background (and thus will not contribute to scattering). This work is being presented at the NPAL workshop.

8. Ambient noise level change due to ocean acidification

A simplified model of ambient shipping noise in the ocean has been developed (together with T. Duda). Large changes in upper-ocean absorption coefficient predicted to follow carbon dioxide uptake into the ocean from the atmosphere have been modeled to have a small but potentially detectable impact on ocean acoustic noise at 100 to 1000 Hz. However, these changes will be below the audibility threshold. The model predicts that a few decibels of increase may occur in 100 years in some very quiet areas very far from noise sources, with small effects in areas closer to noise sources. A paper [7] has been published and the work was presented at 158th ASA Meeting in San Antonio, TX.

RESULTS

Significant progress has been made on the development of a theory of acoustic scattering in long-range deep ocean propagation, especially the scattering of sound near the sound channel axis. The LOAPEX data shows generally good agreement between observations and theory. We have improved our understanding of the influence of the background sound speed structure on the resulting wave field fluctuations. Also some progress has been made on extending the existing theory to the environments with strong range dependence. In addition, a study of oceanic acoustic response to acidification has been made.

IMPACT/APPLICATIONS

The research described here has both scientific and operational applications. This work is contributing to an improved understanding and field verification of the basic physics of low-frequency long-range sound propagation in the ocean which is important in long-range tomographic systems, communication, and surveillance. Also, this knowledge contributes to an understanding of the limitations of advanced signal processing techniques, such as matched field processing.

TRANSITIONS

These results are being used to interpret the data collected during LOAPEX experiment. They also may be used for interpretation of previously collected data in the SLICE89, AET and SPICE04 experiments. We are unaware of transitions to system applications.

RELATED PROJECTS

The PI and collaborators listed above actively collaborate with many ONR-sponsored researchers who work on projects related to NPAL and participate in the NPAL workshops.

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PUBLICATIONS

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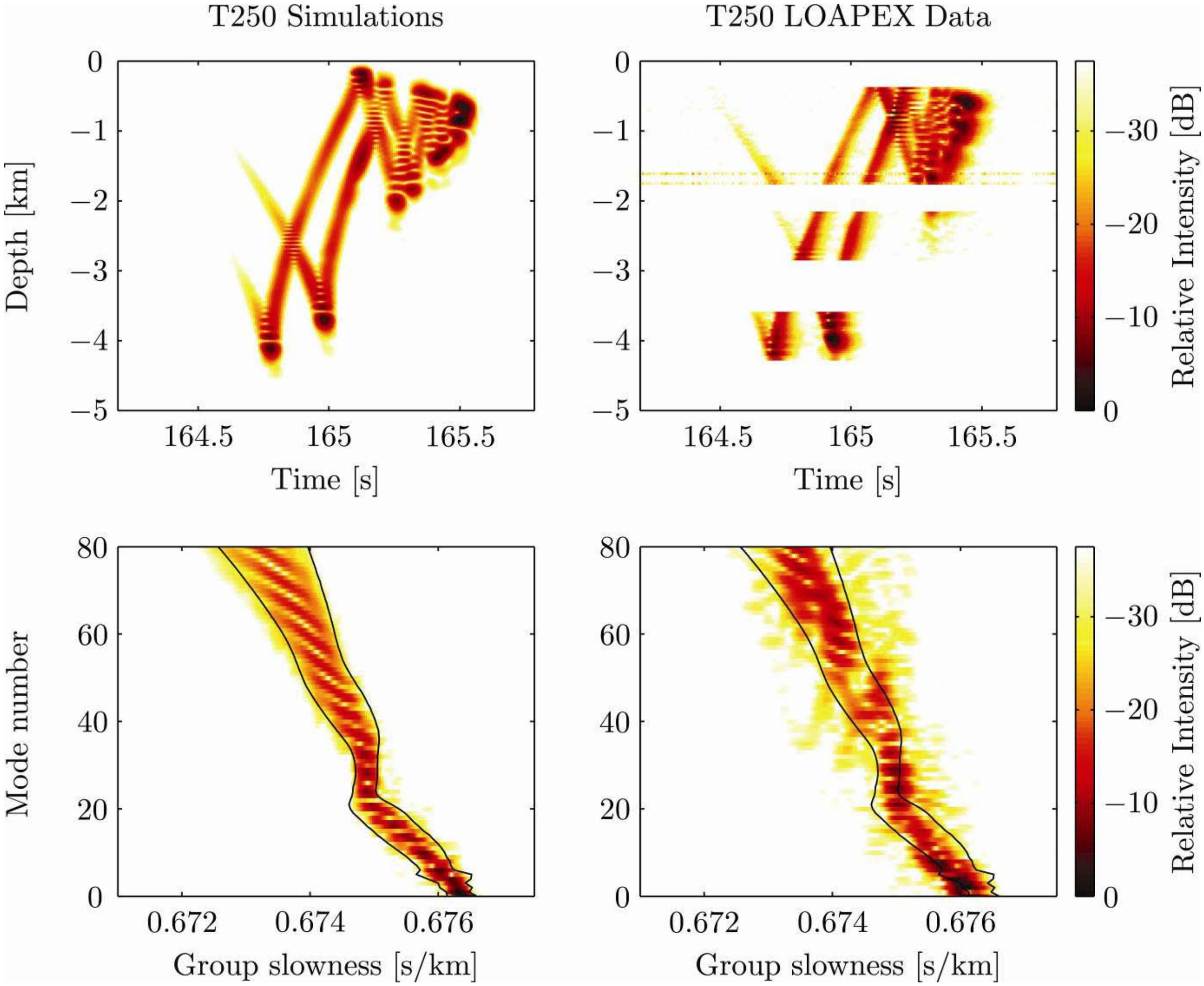

Figure 1. (upper panels) Simulated (left) and measured (right) LOAPEX wave fields in* (z,t) *at a range of approximately 250 km. The simulated wave field was constructed using an environment including an internal-wave-induced sound speed perturbation. (lower panels) The corresponding mode-processed wave fields in (m,S_g) where t = S_g r. Theoretical bounds on the predicted time spread are shown using solid lines. Note the mismatch between the mode processed data wave field and theoretical predictions.

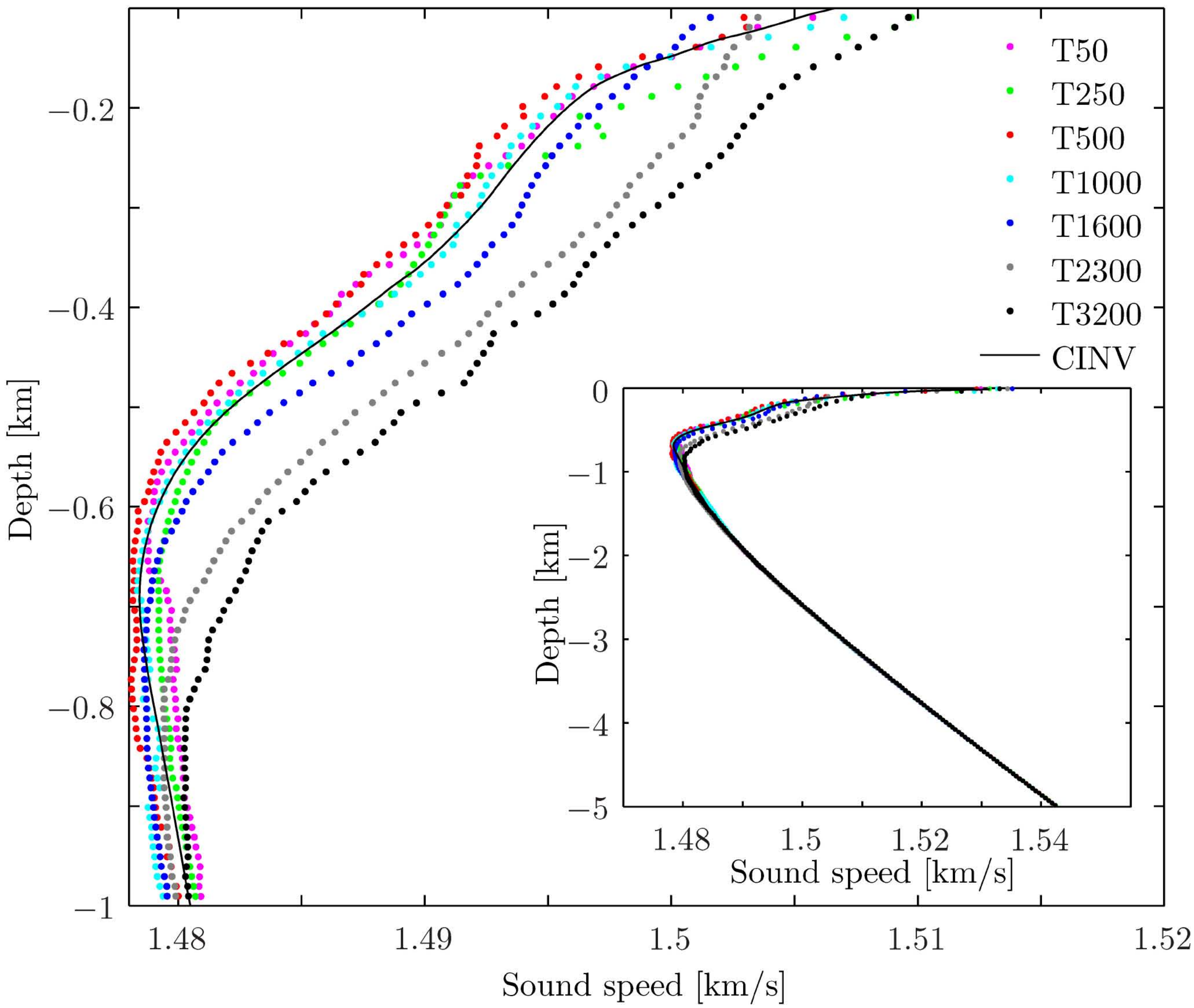

Figure 2. Sound speed profiles at each of the seven transmission stations, T50, T250, T500, T1000, T1600, T2300 and T3200, and the inverted profile (CINV). The use of CINV profile for mode processing results in a significant reduction of a mismatch between data and theoretical prediction seen in Fig. 1 (lower right panel).

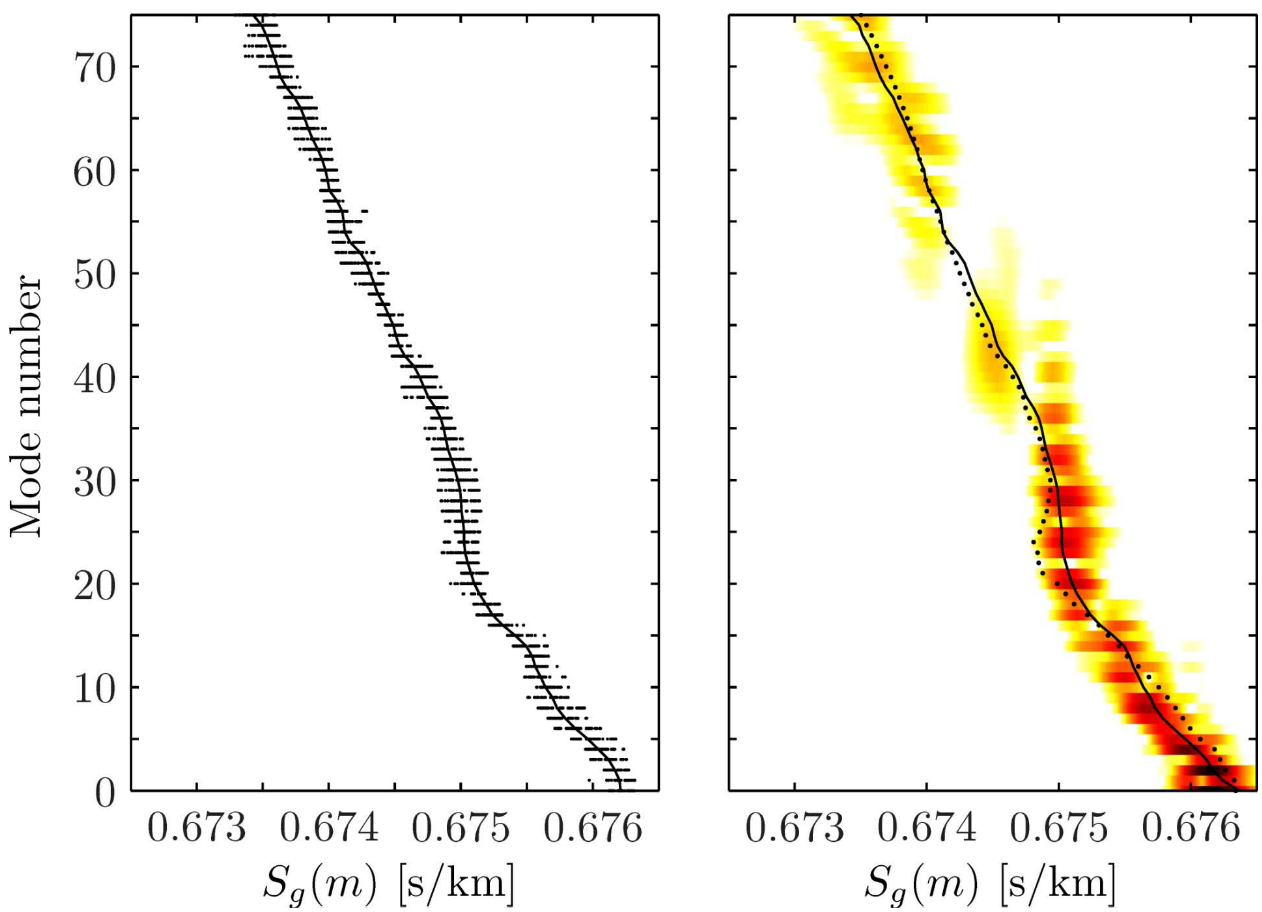

Figure 3.(left panel) Estimates of group slownesses at 75Hz derived from 45 realizations of mode-processed wave fields corresponding to T250, T500 and T1000 LOAPEX transmissions (dots); and the smoothed (in m) set of estimates (solid curve) that were used as input to the inversion algorithm. (right panel) Mode-processed LOAPEX wave field corresponding to a T250 transmission produced using piecewise-coherent processing of SVLA and DVLA contributions in the CINV environment. Wave field intensity is plotted on a logarithmic scale with a dynamic range of 30 dB.Two predicted Sg(m; 75 Hz) curves are superimposed: dots correspond to the C SVLA profile; the solid line corresponds to the C INV profile.

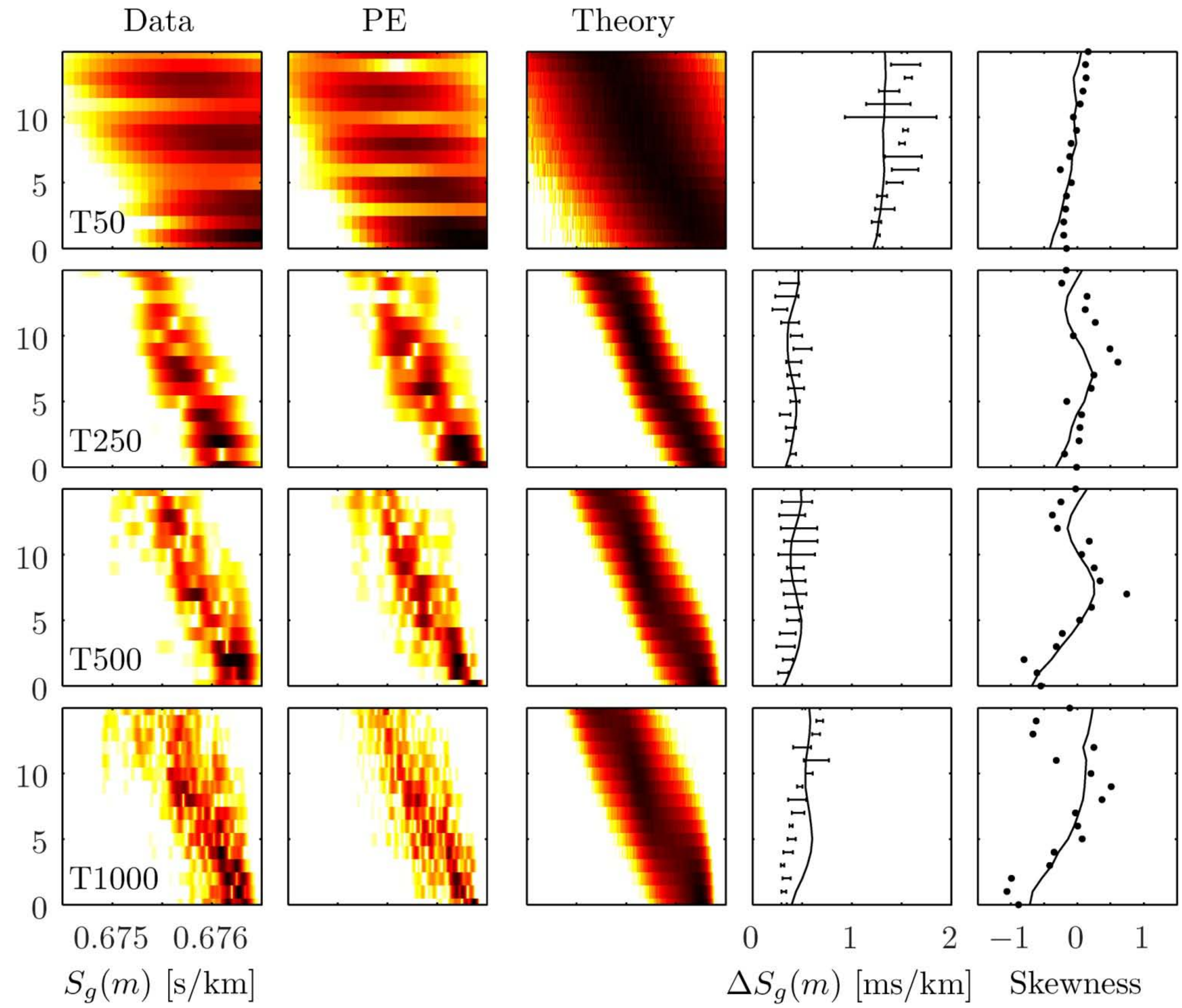

***Figure 4**. Measured and predicted energy distributions in mode-processed wave fields corresponding to a source center frequency of 75 Hz and a source depth of 800 m. First column: measurement-based fields. Second column: full-wave simulation-based fields. Third column: predicted energy distribution based on a simple theory. In each of the three leftmost panels intensity is plotted on a logarithmic scale with a 30 dB dynamic range. Forth column: measured and predicted, based on the simple theory, estimates of time spreads as a function of mode number m. Measurement-based estimates and associated error bars are based on all available good-quality measurements. Fifth column: estimates of skewness based on LOAPEX data (dots) and theoretical predictions (solid lines). Each row corresponds to a different range, with range increasing downwards.*

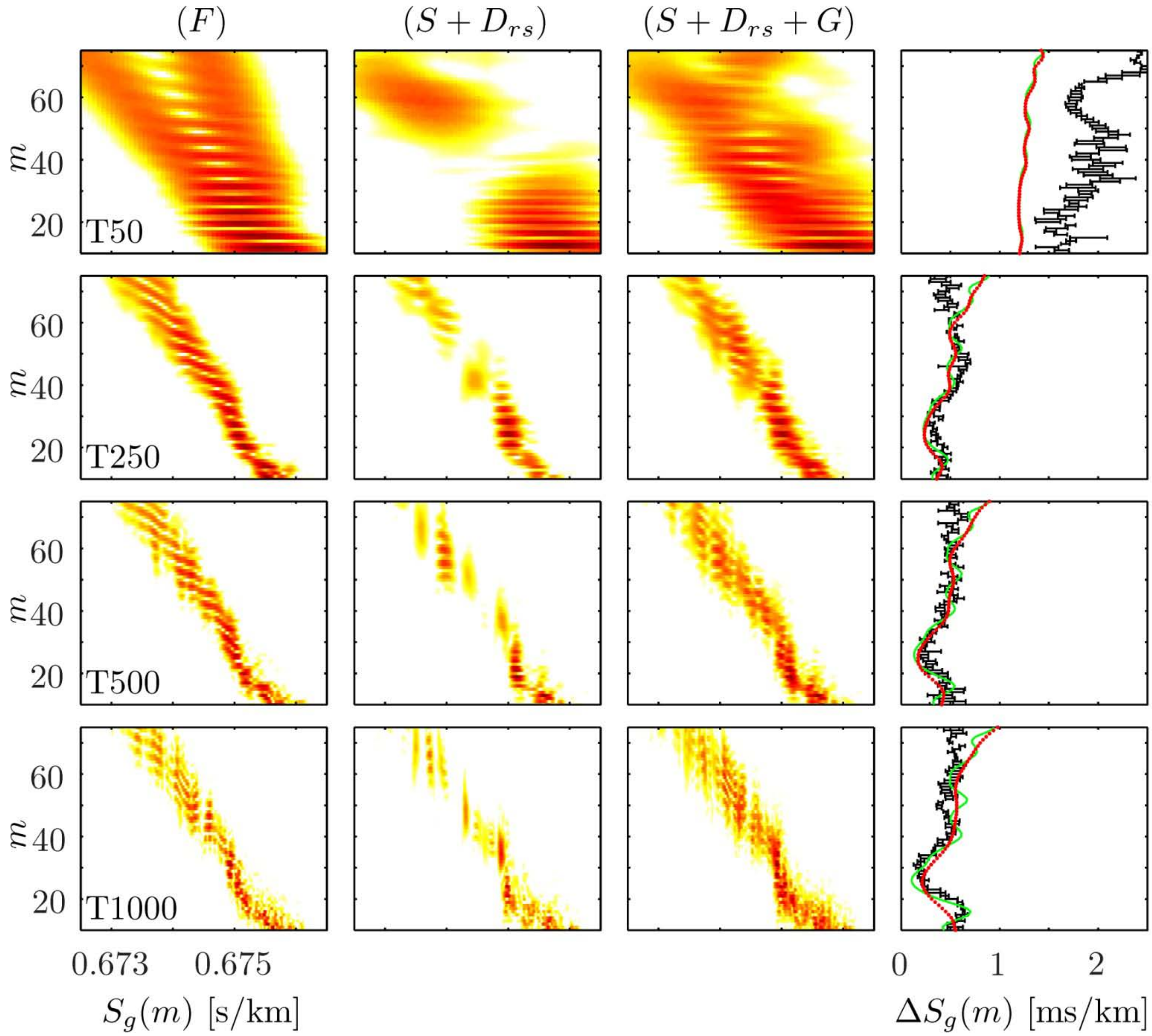

Figure 5 Examples of mode-processed wave fields in (m,S_g) corresponding to 75 Hz transmissions with a source depth of 800 m. Left panels: simulation-based fields. Left- center panels: SVLA/DVLA-based fields produced using piecewise coherent processing. Right-center panels: SVLA/DVLA/gap-based fields produced using piecewise coherent processing. In each of the three leftmost panels intensity is plotted on a logarithmic scale with a 30 dB dynamic range. Right panels: theoretical predictions (green lines), modified theoretical predictions (red lines) and data-based estimates (horizontal error bars) of time spreads at each m. Data-based estimates are based on averages over all available "good" realizations of the wave field. Each row corresponds to a different range, with range increasing downward.